# Higgs Working Group Report

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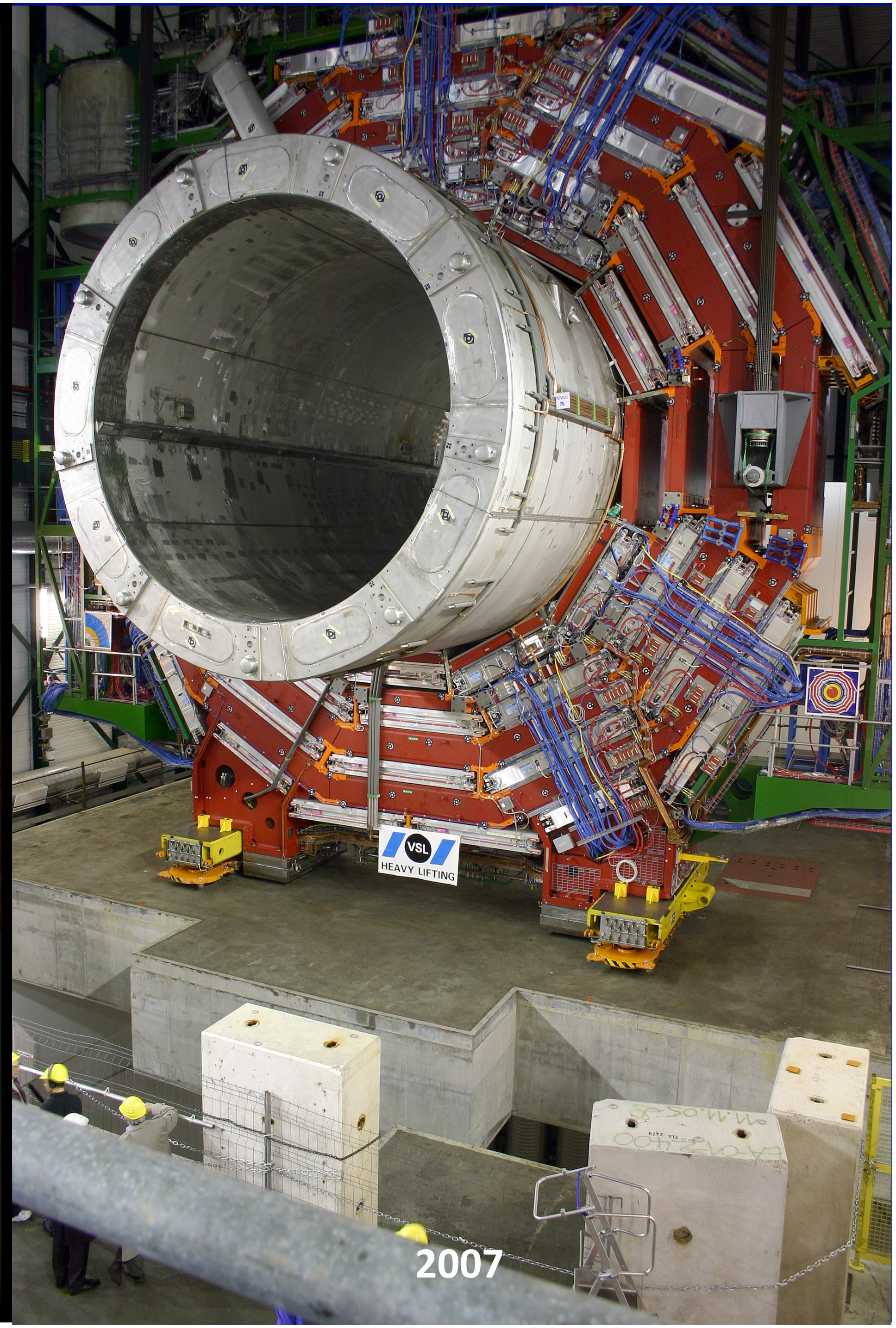
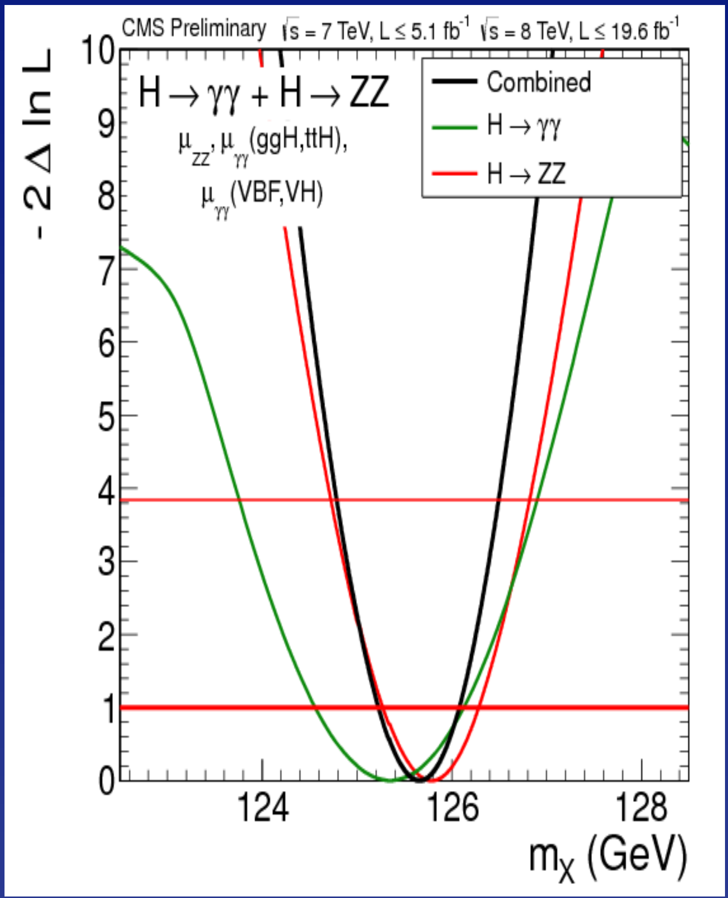
Snowmass Meeting

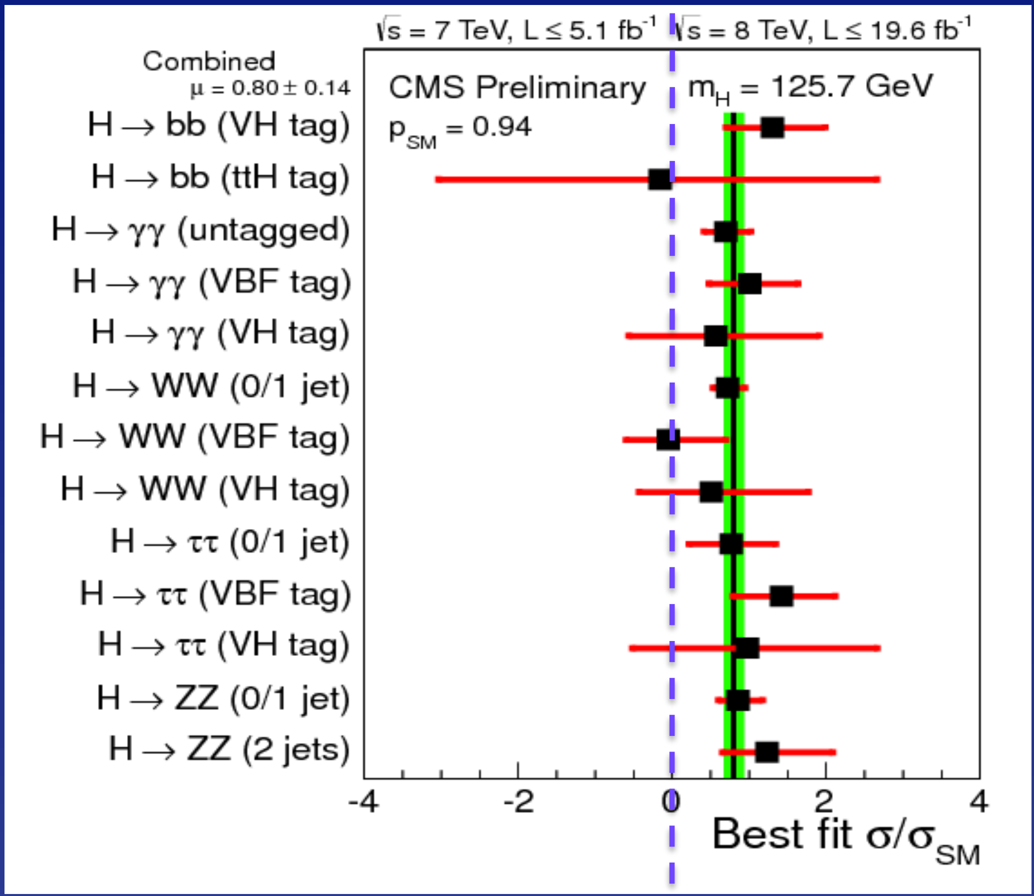
July 30, 2013


1988


VSL
HEAVY LIFTING
2007

# 126 GeV Boson – a permanent addition to the recipe of our Universe




Mass = 125.7 +/- 0.3 +/- 0.3

Has all the general features
we are currently able to test at the LHC

How far can the LHC go? Total width stops us at 15-20%

# New Physics in the Higgs Sector

- Where can new physics enter? (Examples)
  - Deviation in couplings to fermions? Additional degrees of freedom in the Higgs sector that mix boson states or introduce multiple vacuum expectation values or mixed states of the fermion
  - Total width increase? Additional low mass particles that go undetected/unidentified at the LHC
  - Deviation in loop processes ($gg \rightarrow H$, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$)? Additional heavy particles entering loops.

# Primary Conclusion of Higgs Report

- A precision Higgs program necessarily requires:
  - Improvement on $\alpha_s$ and order of magnitude tightening on the precision of on fundamental parameters in Electroweak theory and on elementary masses
    - We gain primarily on the power of theory predictions and we believe that all areas of particle physics will gain from this – we need to collaborate more with EDM/etc to understand what the other demands are outside of Higgs physics
  - High statistics of Higgs production in the ZH production process at a lepton collider - we've received white papers for $e^+e^-$ linear and circular colliders and the muon collider
    - The precision on the total Higgs width in this environment is essential to enable precision tests in the Higgs sector and to challenges the major new physics questions
    - Dedicated s-channel machines ($\gamma\gamma$ and $\mu\mu$) can also make unique contributions

# High Precision Program (Some Examples)

| X | Physics | Present precision | | Challenge |
|---|---|---|---|---|
| **$M_Z$** MeV/c2 | **Input** | 91187.5 ±2.1 | Z Line shape scan | QED corrections |
| **$\Gamma_Z$** MeV/c2 | **$\Delta\rho$ (T) (no $\Delta\alpha$!)** | 2495.2 ±2.3 | Z Line shape scan | QED corrections |
| **R** | $\alpha_s$ , $\delta_b$ | 20.767 ± 0.025 | Z Peak | QED corrections |
| **$N_\nu$** | **Unitarity of PMNS, sterile $\nu$'s** | 2.984 ±0.008 | Z Peak | **QED corrections to Bhabha scat.** |
| **$R_b$** | $\delta_b$ | 0.21629 ±0.00066 | Z Peak | Hemisphere correlations |
| **$A_{LR}$** | **$\Delta\rho$, $\varepsilon_3$ ,$\Delta\alpha$ (T, S )** | 0.1514 ±0.0022 | Z peak, polarized | Design experiment |
| **$M_W$** MeV/c2 | **$\Delta\rho$, $\varepsilon_3$ , $\varepsilon_2$, $\Delta\alpha$ (T, S, U)** | 80385 ± 15 | Threshold scan | |
| **$m_{top}$** MeV/c2 | **Input** | 173200 ± 900 | Threshold scan | Theory limit at 100 MeV? |

Few $10^{-6}$ on $\sin^2\theta_W$

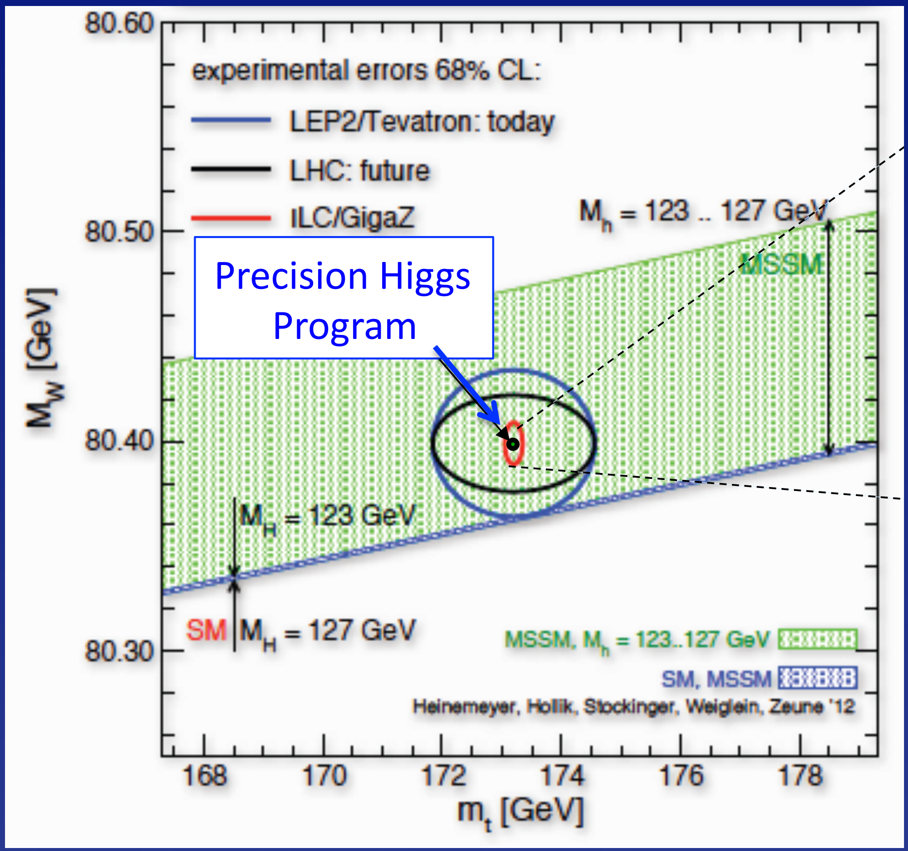
Sub-MeV Z/W/top masses

Improved $\alpha_s$

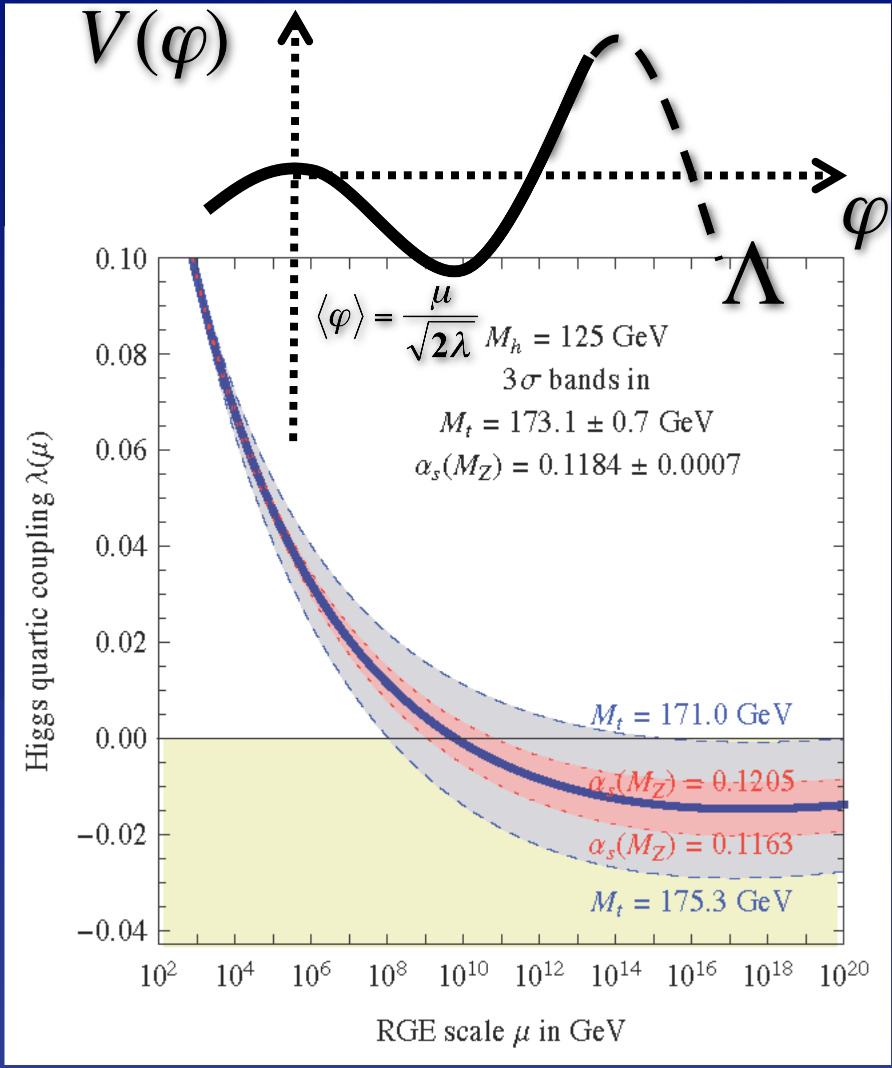
Tightening on # of $\nu$'s

GOAL: An order of magnitude improvement on fundamental parameters

# Reaches well beyond Higgs Physics




Agreement with the Standard Model becomes a speck in this plot



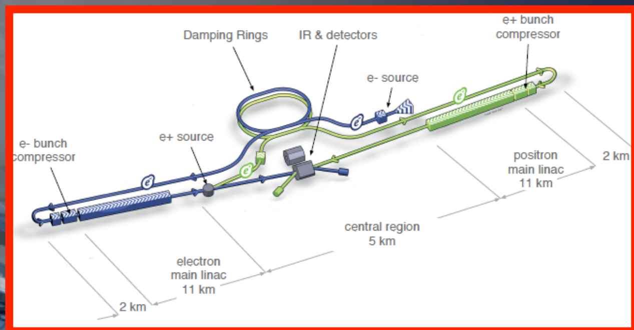

Is the final stopping point in the expansion of the universe – the Higgs vacuum decay?

# Precision Higgs Program

- Coupling measurements
- Double Higgs production and the Higgs self-coupling
- Study of CP-mixture and spin
- Mass and Total Width measurements
- Direct searches for Beyond-the-SM Higgs Bosons
- Conclusions
  - Highlighting outcomes of the report
  - Facility comparisons for this physics

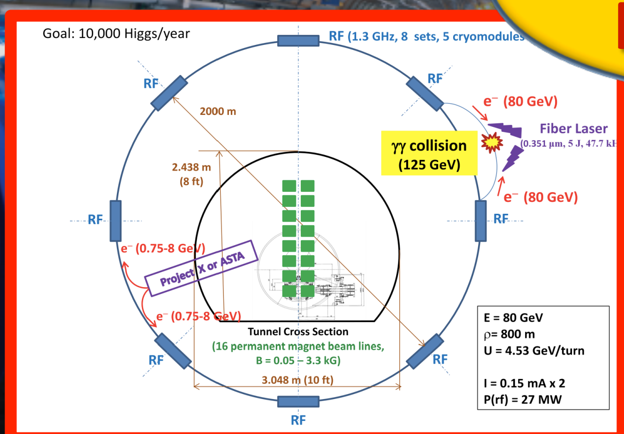
# From Higgs studies and electroweak high precision tests…

## Linear Colliders
(ILC, CLIC)



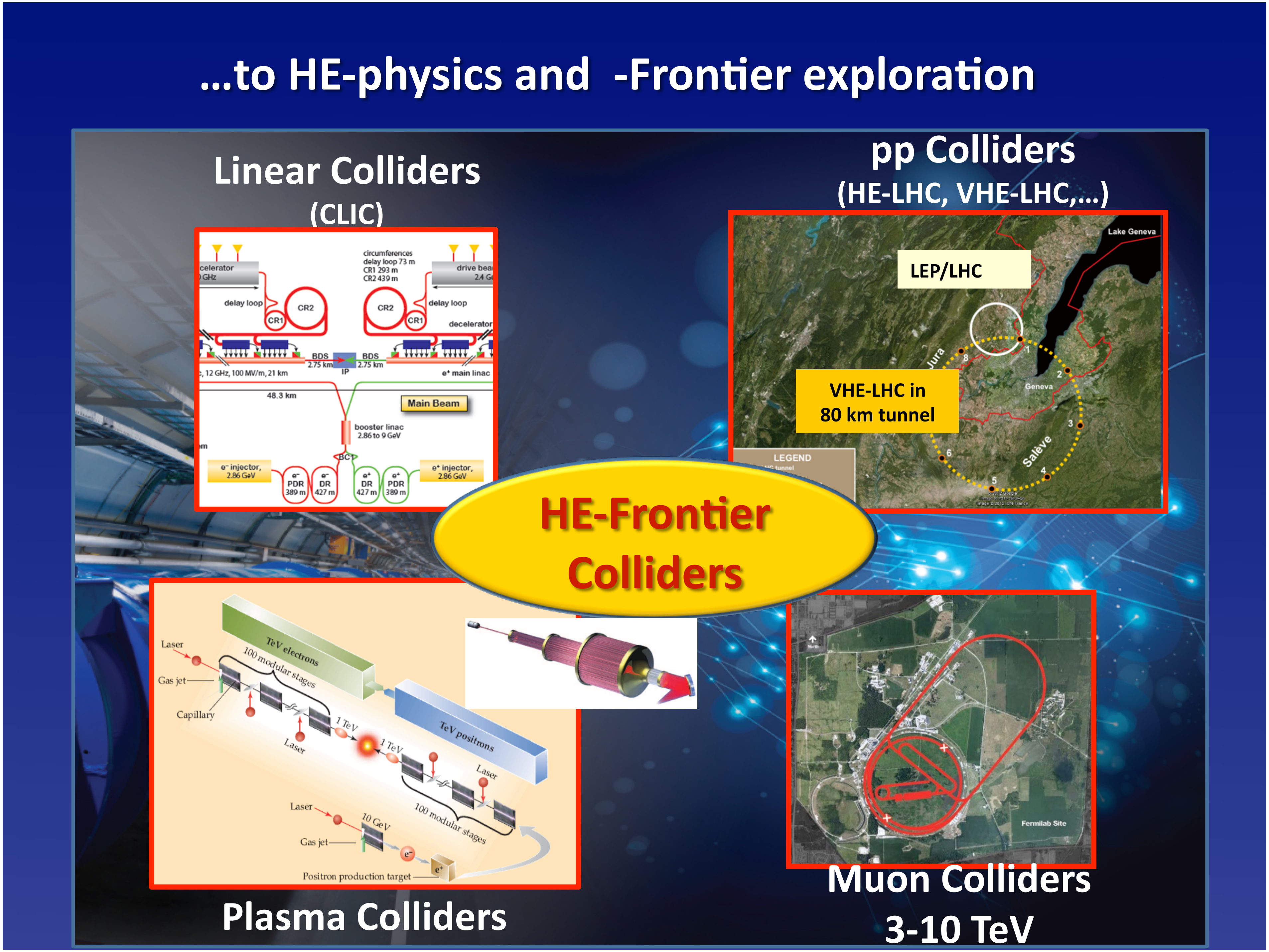

## Circular $e^+e^-$ Colliders
(TLEP, super TRISTAN, IHEP…)


**Higgs Factories**




## $\gamma\gamma$ Colliders
(HFiTT ,CLICHE, SAPPHIRE, SILC )


## Muon Colliders
($\nu$-Fact. as possible 1st step)


...to HE-physics and -Frontier exploration
Linear Colliders
(CLIC)
pp Colliders
(HE-LHC, VHE-LHC,...)
LEP/LHC
VHE-LHC in 80 km tunnel
Lake Geneva
Geneva
Jura
Saleve
LEGEND
HE-Frontier Colliders
Main Beam
booster linac 2.86 to 9 GeV
delay loop
CR1
CR2
BDS 2.75 km
IP
48.3 km
e⁻ injector, 2.86 GeV
e⁺ injector, 2.86 GeV
e⁺ main linac
circumferences delay loop 73 m CR1 293 m CR2 439 m
decelerator
TeV electrons
TeV positrons
100 modular stages
Laser
Gas jet
Capillary
1 TeV
10 GeV
Positron production target
Fermilab Site
Plasma Colliders
Muon Colliders
3-10 TeV

# Higgs Coupling Measurements

| Facility | LHC | HL-LHC | ILC | ILC LumiUP | CLIC | TLEP (4 IPs) |
|---|---|---|---|---|---|---|
| Energy (GeV) | 14,000 | 14,000 | 250+500+1000 | 250+500+1000 | 350+1400+3000 | 240+350 |
| $\int \mathcal{L}dt$ ($\mathrm{fb}^{-1}$) | 300/expt | 3000/expt | 250+500+1000 | 1150+1600+2500 | 500+1500+2000 | 10000+1400 |
| $N_H$ ($\times 10^6$) | 17 | 170 | 0.37 | 1.05 | 2.2 | 3.2 |
| Measurement precision | | | | | | |
| $m_H$ (MeV) | 100 | 50 | 35 | 35 | 33 | 7 |
| $\Delta\Gamma_H$ | – | – | 4.8/1.6/1.2% | tbd | ? | 0.5% |
| $\mathrm{BR}_{\mathrm{inv}}$ | $< 14 - 18\%$ | $< 7 - 11\%$ | <0.44/0.30/0.26% | tbd | tbd | <0.1% |
| $\Delta g_{H\gamma\gamma}$ | $5 - 7\%$ | $2 - 5\%$ | 4.9/4.3/3.3% | tbd | –/5.5/<5.5% | 1.5% |
| $\Delta g_{HZ\gamma}$ | $41 - 41\%$ | $10 - 12\%$ | ? | ? | tbd | tbd |
| $\Delta g_{Hgg}$ | $6 - 8\%$ | $3 - 5\%$ | 4.0/2.0/1.4% | tbd | 3.6/0.79/0.56% | 0.79% |
| $\Delta g_{HWW}$ | $4 - 6\%$ | $2 - 5\%$ | 1.9/0.24/0.17% | tbd | 1.5/0.15/0.11% | 0.10% |
| $\Delta g_{HZZ}$ | $4 - 6\%$ | $2 - 4\%$ | 0.44/0.30/0.27% | tbd | 0.49/0.33/0.24% | 0.05% |
| $\Delta g_{H\mu\mu}$ | update | update | –/–/16% | tbd | –/10/5.2% | 6.2% |
| $\Delta g_{H\tau\tau}$ | $6 - 8\%$ | $2 - 5\%$ | 3.3/1.9/1.4% | tbd | 3.5/1.4/<1.3% | 0.51% |
| $\Delta g_{Hcc}$ | – | – | 4.7/2.5/2.1% | tbd | 3.1/1.1/0.75% | 0.69% |
| $\Delta g_{Hbb}$ | $10 - 13\%$ | $4 - 7\%$ | 2.7/0.94/0.69% | tbd | 1.7/0.32/0.19% | 0.39% |
| $\Delta g_{Htt}$ | $14 - 15\%$ | $7 - 10\%$ | 14/9.3/3.7% | tbd | –/4.0/<4.0% | 13% |
| $\Delta g_{HHH}$ | – | 50% | 26% | 16% | 16/10% | – |

**LHC must assume SM decay modes and dashes indicate 2nd gen couplings**

**Improvement factors of x3-x10 are possible (much more without SM assumptions)**

Muon Collider is expected to have a similarly rich physics program as an $e^+e^-$ collider – more detailed simulation studies are needed. γγ colliders also have coupling numbers.

# Higgs $e^+e^-$ Factory Comparison

## Nominal Linear (ILC 250-500 GeV) vs. Circular (TLEP 240-350 GeV)

Improvement Factor

**Improvement over LHC is much larger when SM assumptions are dropped**

| Facility | ILC | TLEP (4 IP) | (Lin/HL-LHC) | (Circ/HL-LHC) | (Circ/Lin) |
|---|---|---|---|---|---|
| Energy (GeV) | 500 | 350 | | | |
| $\int \mathcal{L}dt$ (fb$^{-1}$) | +500 | +1400 | | | |
| $\Delta\Gamma_h/\Gamma_h$ | 6.0% | 0.6% | ~x100 or more | ~x1000 or more | x10 |
| $\mathcal{B}_{\rm inv}$ | $< 0.69\%$ | $< 0.1\%$ | ~x14 or more | ~x100 or more | x7 |
| $\Delta g_\gamma/g_\gamma$ | 8.4% | 1.5% | x(1/7)-x1 | x1-x3 | x5 |
| $\Delta g_{Z\gamma}/g_{Z\gamma}$ | ? | ? | | | |
| $\Delta g_g/g_g$ | 2.5% | 0.8% | x1-x2 | x3-x6 | x3 |
| $\Delta g_W/g_W$ | 1.4% | 0.19% | x1-x2 | x10-x26 | x7 |
| $\Delta g_Z/g_Z$ | 1.3% | 0.15% | x1-x3 | x13-x33 | x8 |
| $\Delta g_\mu/g_\mu$ | – | 6.2% | - | x1-x2 | TLEP-only |
| $\Delta g_\tau/g_\tau$ | 2.5% | 0.54% | x1-x2 | x3-x9 | x4 |
| $\Delta g_c/g_c$ | 3.0% | 0.71% | ($e^+e^-$ only) | ($e^+e^-$ only) | x4 |
| $\Delta g_b/g_b$ | 1.8% | 0.42% | x2-x4 | x9-x16 | x4 |
| $\Delta g_t/g_t$ | 18% | 13% | x(1/2) | x(1/2)-x1 | ~Same |

http://www.snowmass2013.org/tiki-index.php?page=The+Higgs+Boson

# Double Higgs production and Higgs Self-Coupling

- Difficult to measure at all facilities
  - best at CLIC (10% precision) and 1 TeV ILC-up (16%)
- High energy 100 TeV pp collider has largest potential to make percent-level measurements
  - Just based on cross section (x50 over LHC)
- γγ Collider is investigating HH at √s=290 GeV

| | HL-LHC | ILC500 | ILC1000 | ILC1000-up | CLIC1400 | CLIC3000 | VLHC |
|---|---|---|---|---|---|---|---|
| $\Delta g_{hhh}/g_{hhh}$ | 50% | 88% | 25% | 16% | 28/21% | 16/10% | ? |

**Table 1-21.** *Expected per-experiment precision of the triple-Higgs boson coupling. ILC1000-up is the luminosity upgrade with 2500 fb$^{-1}$ at 1000 GeV. The two numbers for each CLIC energy are without/with 80% electron beam polarization.*

# CP-Mixture and Spin

- Highest CP sensitivity at a $\gamma\gamma$ collider
  - And potentially at muon collider with polarization
- Tau-lepton polarization at $e^+e^-$ colliders

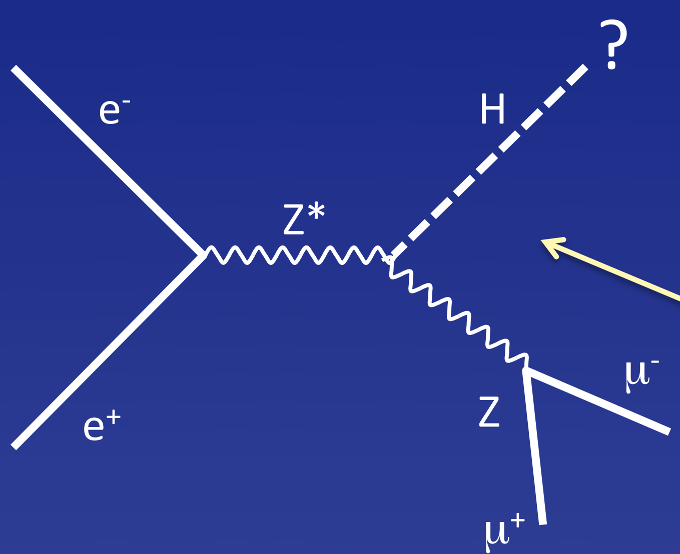
| Facility | LHC | HL-LHC | $e^+e^-$ | $e^+e^-$ | $e^+e^-$ | $\mu^+\mu^-$ | $\gamma\gamma$ | target |
|---|---|---|---|---|---|---|---|---|
| Energy (GeV) | 14,000 | 14,000 | 250 | 500 | other | ? | 126 | (theory) |
| $\int \mathcal{L}dt$ (fb$^{-1}$) | 300/expt | 3000/expt | 250 | 500 | other | ? | ? | |
| spin-$2^+_m$ | $\sim 10\sigma$ | $\gg 10\sigma$ | $>10\sigma$ | $>10\sigma$ | | ✓ | ✓ | $>5\sigma$ |
| ... | ... | ... | ... | ... | ... | ... | ... | |
| $ZZH$ | 0.07† | 0.02† | 0.0008 | 0.00005 | | ✓ | ✓ | $< 10^{-5}$ |
| $WWH$ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | $< 10^{-5}$ |
| $ggH$ | ? | ? | – | – | | – | – | $< 10^{-2}$ |
| $\gamma\gamma H$ | – | ? | – | – | | – | $< 0.01$ | $< 10^{-2}$ |
| $Z\gamma H$ | – | ? | – | – | | – | – | $< 10^{-2}$ |
| $\tau\tau H$ | ? | ? | 0.01 | 0.01 | | ✓ | ✓ | $< 10^{-2}$ |
| $ttH$ | ✓ | ✓ | – | ✓ | | – | – | $< 10^{-2}$ |
| $\mu\mu H$ | – | – | – | – | | ✓ | – | $< 10^{-2}$ |
| $bbH$ | – | ? | ? | ? | | – | – | $< 10^{-2}$ |

† estimated only in $H \to ZZ^*$ decay mode.

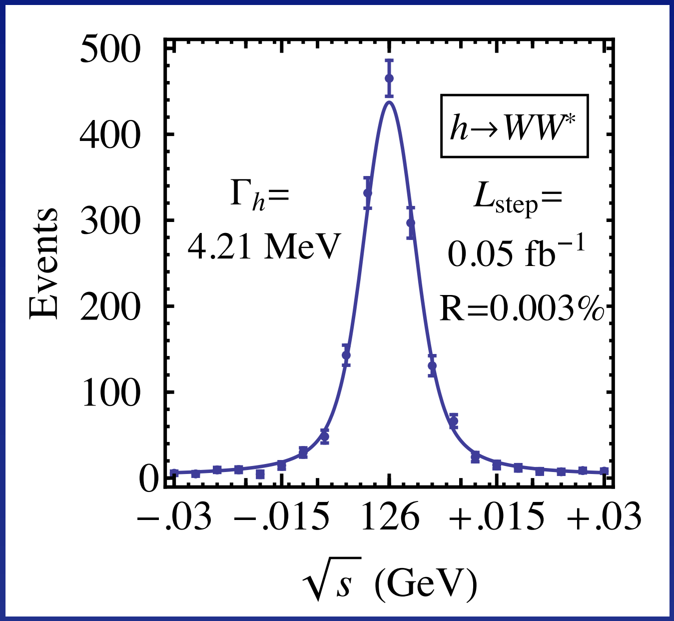
# Z – tagging by missing mass at an $e^+e^-$ collider

total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
→measure total width $\Gamma_H$
($\nu\nu$H is used to get H→ZZ statistics)

empty recoil = invisible width
'funny recoil' = exotic Higgs decay




# Muon collider Lineshape scan




Precision of percent to sub-percent on Higgs total width

Need High Statistics for Z boson dilepton decay mode

# Mass and Total Width Measurements

- LHC is not able to make sub-GeV constraints on the Higgs width (predicted to be ~4 MeV)
- $e^+e^-$ colliders are limited by statistics in ZH production and can achieve 0.6-11%
- Muon collider has unique lineshape scan capability (1.7-17%)

| | LHC | HL-LHC | ILC250 | Full ILC | ILC LumUp | CLIC | TLEP (4 IP) | $\mu$C |
|---|---|---|---|---|---|---|---|---|
| $m_h$ (MeV) | 100 | 50 | 35 | 35 | ? | 33 | 7 | 0.03–0.25 |
| $\Delta\Gamma_h$ | – | – | 11% | 5.6% | 2.7% | 8.4% | 0.6% | 1.7–17% |

**Table 1-24.** *Summary of of the Higgs mass and total width measurement capabilities of various facilities. "Full ILC" is 250+500+1000 GeV with 250+500+1000 fb$^{-1}$, while "ILC LumUp" is 1150+1600+2500 fb$^{-1}$ at the same collision energies.*

# Direct searches for Beyond-the-SM Higgs Bosons

- $e^+e^-$ Collider - mass reach up to half of center-of-mass energy (500 GeV ILC, 1.5 TeV CLIC):

$$M_{H^+} < \sqrt{s}/2, \qquad M_{H^0} + M_{A^0} < \sqrt{s}.$$

- Muon Collider – Possibility of resonance production – mass reach up to center-of-mass energy can to to Multi-TeV
- HL-LHC will potentially exclude MSSM Higgs sector that is within the reach of a 1 TeV ILC (with di-tau and VV decays)
- 100 TeV pp Collider has highest mass reach

# Major Challenges for Higgs Physics

- The LHC at 14 TeV will probe new physics at and above the TeV scale in a broad sweep
  - Beyond the LHC, the most promising avenue for future exploration is via the Higgs boson properties through high precision measurement.
    - What precision needs to be achieved to challenge our understanding of the universe and the laws of physics?
- The Higgs boson and the top quark were guaranteed discoveries based on exactly this strategy
  - The basis for the high precision measurements came from the Z factories (over $10^6$ Z bosons produced on resonance and studied with polarized beams).

# A Future Direction

- A precision Higgs physics program is compelling because the Standard Model precisely predicts all Higgs boson couplings and properties with no free parameters, now that the Higgs mass is known.
  - There is a vision for a precision Higgs program:
    - An order of magnitude increase in precision on fundamental parameters at the EW scale, improvement on $\alpha_s$ – and corresponding improvements in theory predictions
    - High statistics Higgs production in the ZH process to achieve a model-independent percent-level precision on the total width
  - Multi-TeV collider technology to pursue higher precision on ttH, Higgs self-couplings, and to pursue the new states that give rise to Higgs coupling deviations (if found)
    - The potential to go after high-$p_T$ physics by embracing the largest technology challenges and energizing the next generation to move orders of magnitude beyond what we can do today